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PROPERTIES OF A YBCO PANCAKE COIL OPERATING WITH AC CURRENT AT FREQUENCIES UP TO 1000 Hz (POSTPRINT)

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Energy/Power/Thermal Division

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14. ABSTRACT
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Properties of a YBCO Pancake Coil Operating With AC Current at Frequencies up to 1000 Hz

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***Abstract*—A small pancake coil was wound using 1.2 m long, 10 mm wide YBCO coated superconductor tape with impregnation by epoxy resin. The coil was immersed in liquid nitrogen and tested in several regimes. In the DC regime, we measured the I-V curve, the hysteresis of the magnetic field-current curve at liquid nitrogen temperature and the radial component of the coil field at the coil edges. The critical currents of a short sample at 77 K were also measured and compared with those of the coil. The AC losses measured in the frequency range from 60 Hz to 1000 Hz are compared with those of a similar coil wound with copper tape. The coil heating due to AC losses was monitored. At 60 Hz, the losses of the YBCO coil were nearly two orders of magnitude lower than those in the Cu coil. With increasing frequency, this difference becomes smaller, but the YBCO coil still exhibited lower losses at 1000 Hz.**

***Index Terms*—Losses, magnetic fields, superconducting magnets.**

I. Introduction

THE APPLICATION of YBCO coated conductors in AC devices is often considered, however, the main focus of industry is currently on the improvement of the DC conductor properties such as critical currents. These conductors have the shape of a flat tape several millimeters wide (typically 4 or 10 mm) with thickness of the order of 0.1 mm [1]. A stack of pancake type coils is preferred to make the application windings when using wide tapes. For coils made with Bi-2223/Ag tapes it was shown that the magnetic anisotropy strongly affects the distribution of the current density inside the tapes [2]. The critical current of the coil is also limited by the largest magnetic field component perpendicular to the tape plane [3]. Since the tape in the pancakes located at the ends of the coil is exposed to an inhomogeneous magnetic field, it is not a straightforward procedure to determine the critical current distribution [4], [5]. Similar problems will also appear in coils wound with YBCO coated conductors.

When conductor is placed in an AC environment, the direction of the magnetic field with respect to the wide face of the tape plays an additional important role. According to Brandt and Indenbom [6], the hysteresis loss in YBCO with a transversely applied magnetic field is directly proportional to the tape width [7]–[9]. Amemiya *et al.* have shown that in the case of an arbitrary orientation of the magnetic field AC losses are proportional to the transverse component of the field [10]. As such, it is important to have information on the AC behavior of coils made of standard, nonstriated YBCO coated conductor. It is of particular interest to obtain AC loss data of a coil at a wide range of frequencies for a better understanding of the AC characteristics of the HTS winding [11]. In this work, we compare the AC behavior of a pancake coil wound with a YBCO coated conductor with that of a similar coil wound of copper tape. Both coils were cooled by liquid nitrogen.

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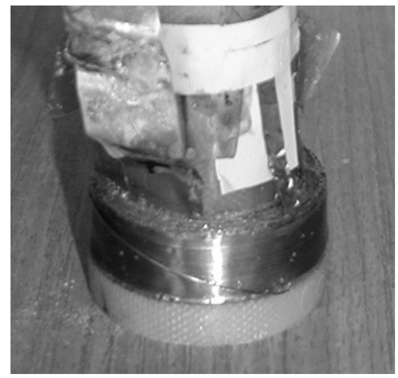

Fig. 1. A photograph of the YBCO coil.

II. Experimental

A. Description of YBCO Coil and Cu Coil

The YBCO coil was made using a 1.2mlength of copper-stabilized YBCO coated conductor. It was co-wound with wet, epoxy-saturated fiberglass cloth on a G10 coil form, and had an inner and outer diameter of 25.8 mm and 33.8 mm, respectively, after completion. The total number of turns in the winding was 13. Fig. 1 is a photograph of the coil.

The conductor was made using a RABIT's architecture: Ni-5 at% W substrate with a sputtered Y_2O_3 seed layer, a YSZ barrier layer, and a CeO_2 cap layer [12], [13]. The substrate had a Curie temperature of $\sim$ 60°C and is ferromagnetic at 77 K [14], which may contribute to the coil's inductance. The 0.8 μm YBCO layer was deposited using a TFA-based solution process and subsequently capped with a 3 μm Ag layer to which a 50 μm thick Cu foil was laminated. The copper coil was made using a $\sim$ 110 μm thick, 1.26mlong copper tape, 10 mm wide, with a resistivity of 1.8×10^{-7} Ωcm at 77 K.

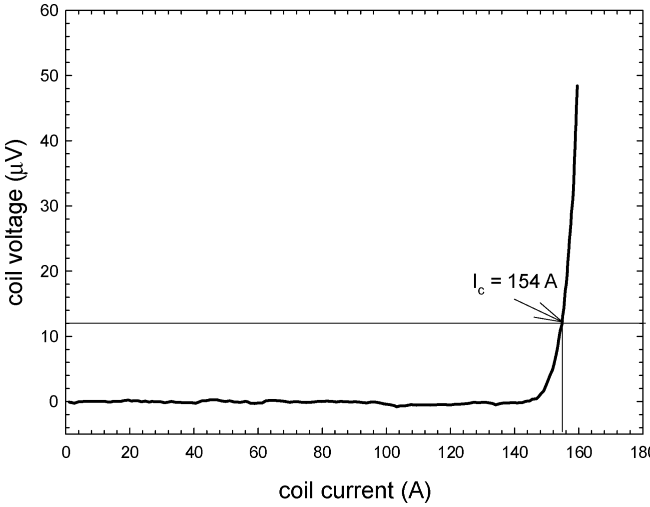

Fig. 2. I-V curve of the coil with a DC current, at 77 K.

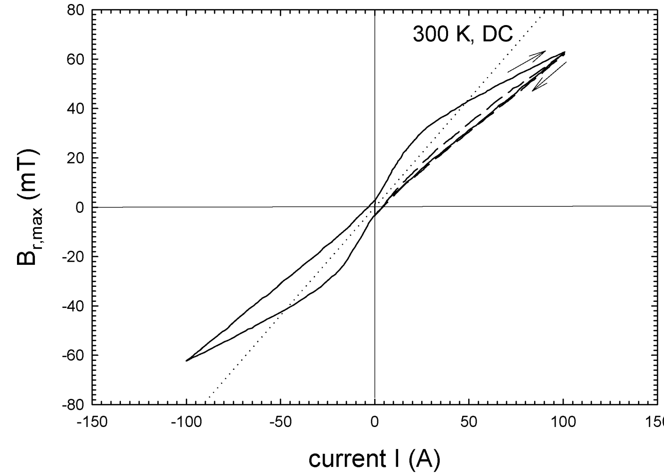

Fig. 4. Maximal values of the radial field component $\mathrm{B_{r,max}}$ (atr $= 15$ mm) as a function of DC current: at room temperature (dotted line), at 77 K and a half cycle $0 \rightarrow 100$ A $\rightarrow 0$ (dashed line) and at 77 K and the full cycle $0 \rightarrow 100$ A $\rightarrow 0 \rightarrow -100$A $\rightarrow 0$ (full lines).

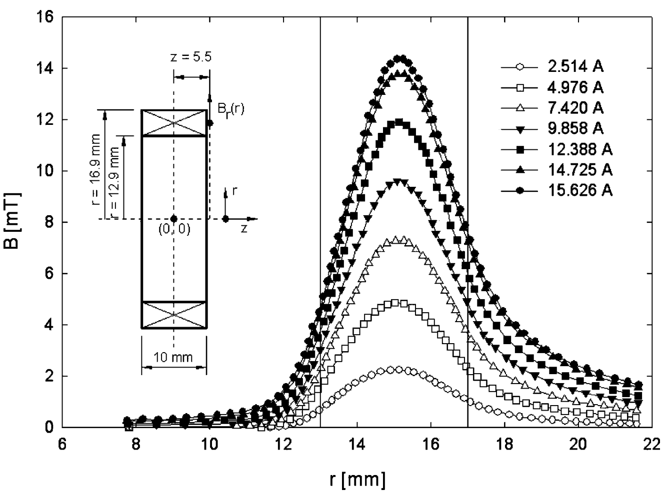

Fig. 3. The radial field component, $\mathrm{B_r}$ as a function of the radial position, r, measured at various current (rms) at 500 Hz.

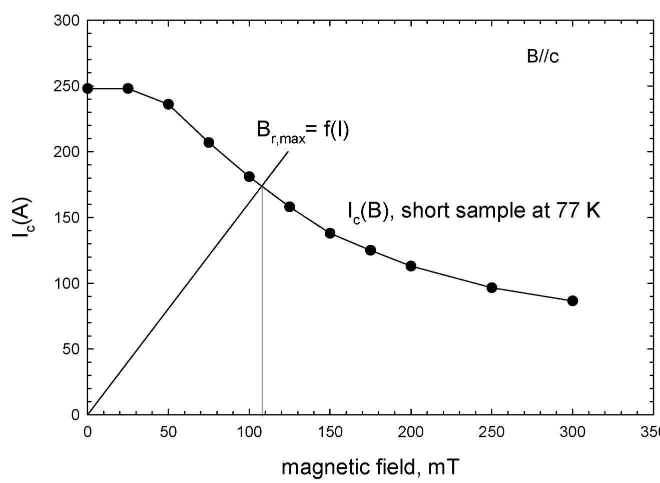

Fig. 5. The load line $\mathrm{B_{r,max}}$ (I) and $\mathrm{I_c(B)}$ curve of the YBCO tape used in the coil.

The number of turns, the inner and outer coil diameter, and the insulation were the same as those of the YBCO coil. A NORMA Power Analyzer 4000D was used to measure the losses of the coil.

III. Results and Discussion

The DC critical current of the coil using a slowly increasing transport current was 154 A for which the coil voltage was 12 μV (see Fig. 2). This corresponds to a mean electric field of 0.1 $\mu\mathrm{V/cm}$ and to a mean winding current density of 5000 $\mathrm{A/cm^2}$. Optimization of the engineering current density of the windings was not considered. At 154 A, the axial field at the coil center, $\mathrm{B_z}(r = 0)$, is 80 mT and at the inner turn of the coil, $\mathrm{B_z}(\mathrm{r} = 20\ \mathrm{mm})$, it is 145 mT calculated assuming a constant current density in the tape.

Using a small active area Hall probe we measured the radial field component, $\mathrm{B_r(r)}$, close to the longitudinal edge of the coil ($\mathrm{z} = 5.5$ mm). In Fig. 3 we show the typical set of $\mathrm{B_r(r)}$ curves measured at 500 Hz and various coil currents. The signal of $\mathrm{B_r(t)}$ was not perfectly sinusoidal. The values of $\mathrm{B_r}$ are its first harmonics. The radial component of the coil field measured at $\mathrm{z} = 5.5$ mm has a maximum, $\mathrm{B_{r,max}}$, at $\mathrm{r_m} \cong 15$ mm (in the middle of the winding thickness). The measurements were repeated with the coil in the normal state (300 K) and at 77 K. $\mathrm{B_{r,max}}$ is plotted vs. coil current in Fig. 4. The values of $\mathrm{B_{r.\,max}}$ increase linearly with increasing current at 300 K, but at 77 K they have a hysteretic character. This behavior further indicates an inhomogeneous current distribution in the tape.

In Fig. 5, the $\mathrm{B_{r,max}}$ (I) load line represents the maximal radial magnetic field which is directly proportional to the current (the hysteresis seen in Fig. 4 is not taken into account). The $\mathrm{I_c(B)}$ curve represents the critical current of the YBCO conductor when exposed to a uniform external field B that is equal to $\mathrm{B_{r,max}}$. Since the critical current of the coil (154 A) is smaller than the point of intersection of the two curves (173 A), the nonuniformity of the induced magnetic field acting on the tape is an effect that must be considered and that uniform field approximations are not sufficient.

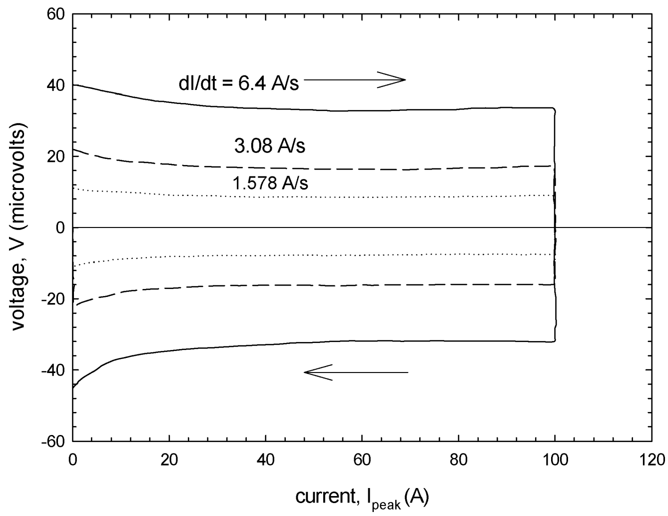

Fig. 6. Coil voltage measured vs. current for triangular current waves with $\mathrm{dI/dt} = 6.4\ \mathrm{A/s}$ (•), $3.08\ \mathrm{A/s}$(○) and $1.578\ \mathrm{A/s}$(◊).

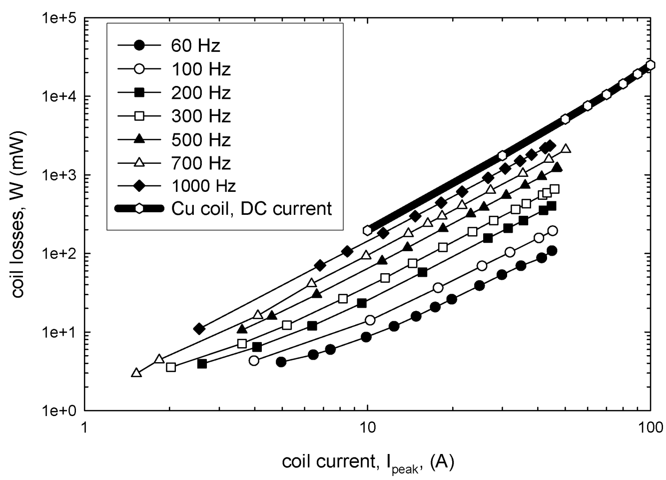

Fig. 7. The measured total AC losses of the YBCO and Cu coils as a function of the coil current Irms at various frequencies from 60 Hz (bottom curve) up to 1000 Hz (upper curve). The losses of Cu coil were measured with DC current.

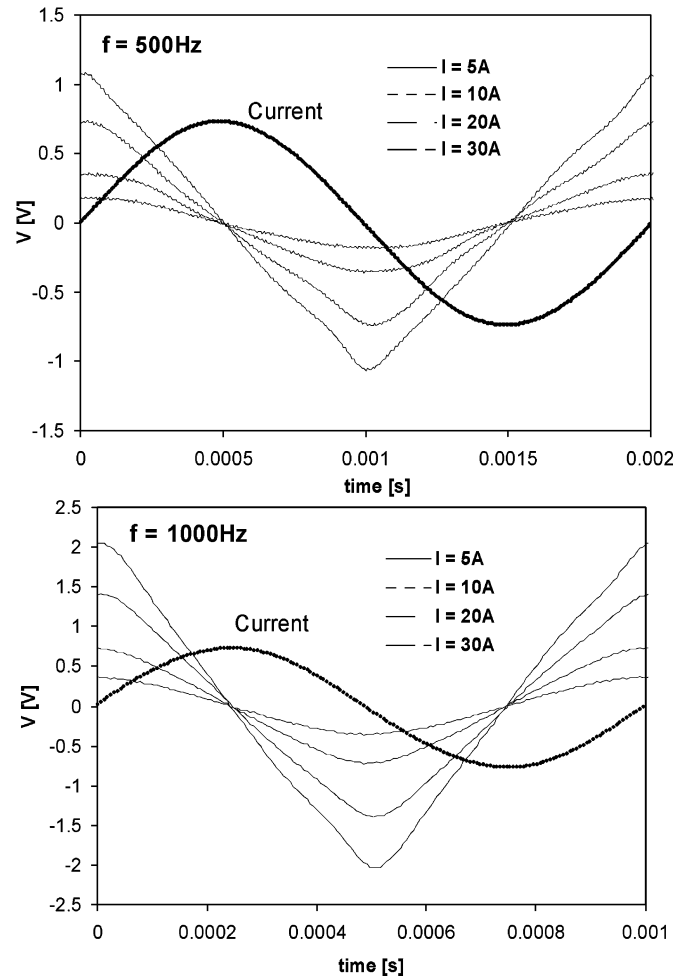

Fig. 8. Coil voltage V vs. time t, measured at 500 Hz and 1000 Hz at various current (rms values).

An initial improvement of this situation could be made by using B_r for a circular current loop, which can be readily expressed, in complete elliptical integrals. One would then integrate the expected critical current across the tape due to this field approximation.

The observed behavior of B_r and its nonuniformity demonstrate the need for new procedures to determine ac losses other than simple extrapolation from short sample data.

To determine the coil inductance, L, we recorded the coil voltage, V, while applying triangular transport current waves with the amplitude of 50 A at frequencies of 50, 100, and $200\mathrm{mHz}$ (Fig. 6). With $\mathrm{V = L\ dI/dt}$, the shape of the curves shows that L depends on the current at low current values, ranging from $\sim\ 7\ \mu\mathrm{H}$ at $\mathrm{I\ =\ 0}$ to $\sim\ 5\ \mu\mathrm{H}$ with increasing currents. At higher currents, L is current independent which independence tends to shift to higher current levels as dI/dt increases.

Loss measurements for the YBCO coil at frequencies from 60 to 1000 Hz are shown in Fig. 7. We also show the losses of the Cu coil with a DC current. There is little difference in losses of the Cu coil between the DC and AC 100 Hz currents. The total losses of both coils increase proportional to $\mathrm{I^n}$, where $\mathrm{n} \cong 1.7$ at a frequency of 60 Hz and $\mathrm{n} \cong 1.9$ at 1000 Hz.

The losses of the copper coil are proportional to I^2 as predicted by theory. However, considerable heating of the Cu coil was observed at larger currents as deduced from the I-V curve, 8.9 K at $\mathrm{I = 100\ A}$.

At 60 Hz, the losses in the YBCO coil are nearly 2 orders of magnitude lower than those in the Cu coil. With increasing frequency, the YBCO coil losses increase and approach the Cu coil losses, but they are still smaller at 1000 Hz. The main components of loss in the YBCO are the hysteresis and self-field losses.

Of particular interest are the nonsinusoidal voltages measured at higher currents, as seen in Fig. 8. The heating of the YBCO coil was monitored by a copper-constantan thermocouple installed in the winding and it was negligible. At 1000 Hz and with an $\mathrm{I_{peak}}$ of 50 A, the temperature increase was below 0.2 K.

IV. Conclusions

In summary, we measured the AC losses in a small YBCO pancake coil and compared it with a similar coil fabricated in the

same fashion using plain copper tape. Due to the magnetization currents, the YBCO coil inductance depends on the coil current. At 60 Hz, the losses of the YBCO coil were nearly two orders of magnitude lower than those in the Cu coil. With increasing frequency, this difference becomes smaller, but the YBCO coil still exhibited lower losses at 1000 Hz. The radial magnetic field component showed that the current distribution in the tape is not uniform. This indicates a need for loss calculation, which is suitable for inhomogeneous fields, and the need for a more ac-tolerant architecture of YBCO conductor.

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